Turbulent drag reduction at high Reynolds numbers

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Abstract

In recent years, spanwise wall oscillation has been shown to attain a drag reduction (DR) as high as 45% [1]. As the previous numerical studies have been confined to low Reynolds numbers, the Reynolds number effect is a requirement in finding out how useful the flow control method is at higher Re numbers [2, 3]. Spanwise wall forcing methods have been studied by applying the following forcing at the wall:

$$w_w(x,t) = W_m \sin\left(\kappa_x x - \omega t\right) \ , \tag{1}$$

where W_m is the maximum wall velocity, κ_x is the streamwise wavenumber and ω is the oscillation frequency. When $\kappa_x = 0$, the forcing becomes the purely temporal wall oscillation case, and the $\omega = 0$ case specifies the purely spatial stationary wave.

In this study, direct numerical simulations of turbulent channel flow subjected to the aforementioned wall forcing technique were performed at four Reynolds numbers with the intention of understanding the relationship between drag reduction and Re. The Reynolds numbers studied correspond to $Re_\tau = 200$, 400, 800 and 1600, based on the no-control case. To the best of the authors' knowledge, this is the highest Re number attempted for flow control DNS [3]. The maximum wall velocity was fixed at $W_m^+ = 12$ for each Re value used, and a range of κ_x^+ and ω^+ were chosen.

Figure 1 shows the drag reduction map in the (ω, κ_x) parameter space at $Re_\tau = 200$ and 400. When comparing the parameters scaled by wall units, the drag reduction was seen to decrease as the Reynolds number increases. The difference, $DR_{400} - DR_{200}$, is shown in Figure 1c). One of the focuses of this work is to see whether the optimal values remain the same at different Reynolds numbers. This helps understand whether the optimal control parameters scale with the wall variables.

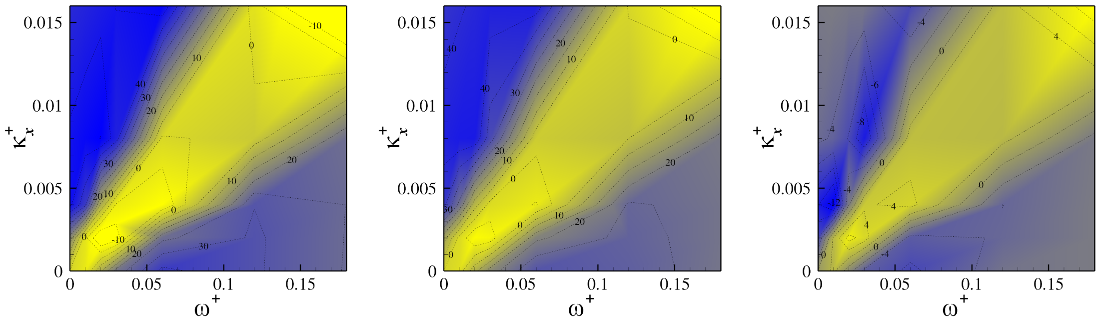

Figure 1: Drag reduction map for the forward travelling waves at (a) $Re_\tau = 200$, (b) $Re_\tau = 400$, and (c) $DR_{400} - DR_{200}$. Contour levels are drawn at 5% intervals. The bright (yellow) colour indicates a drag increase, and the dark (blue) indicates a drag reduction.

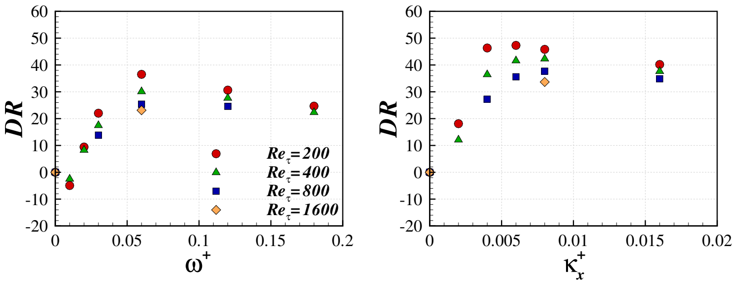

Figure 2: Drag reduction at the four Reynolds numbers studied for (a) the wall oscillation case, $\kappa_x^+ = 0$, and (b) the stationary wave case, $\omega^+ = 0$.

(a)

ω^+	0.03	0.06	0.12
α	0.31	0.26	0.14

(b)

κ_x^+	0.004	0.006	0.008
α	0.38	0.18	0.13

(c)

ω^+	0.01	0.02	0.03
α	0.17	0.22	0.38

(d)

κ_x^+	0.004	0.008	0.016
α	0.38	0.22	0.11

Table 1: $DR \sim Re_\tau^{-\alpha}$ scalings for (a) wall oscillation, (b) the stationary wave, (c) travelling wave with $\kappa_x^+ = 0.008$, and (d) travelling wave with $\omega^+ = 0.02$.

The Reynolds number effect of the wall oscillation and stationary wave cases is shown Figure 2 for Reynolds numbers up to $Re_\tau = 1600$. It is evident that the optimal control parameters change also with Re number. When comparing the parameters scaled by wall units, the optimal κ_x^+ value for the stationary wave case appears to increase with the Re number while the changes in the optimal ω^+ for the wall oscillation case is less prominent [3]. The optimal value for the stationary wave, based on the parameters studied, varies from $\kappa_x^+ = 0.006$ at $Re_\tau = 200$ to $\kappa_x^+ = 0.008$ by $Re_\tau = 400$ whilst the optimal oscillation frequency remains at $\omega^+ = 0.06$, corresponding to $T^+ = 100$.

From Figures 1 and 2, it is found that the drag reduction decreases as the Reynolds number increases. However, the extent of the variation is dependent on ω^+ and κ_x^+. The Reynolds number effect can be expressed in the form of $DR \sim Re_\tau^{-\alpha}$; a large α value indicates a strong Re effect, *i.e.*, a smaller drag reduction. Table 1 shows scalings calculated from the DNS results at different values of ω^+ and κ_x^+ parameters. A wide range of α values are observed in the travelling wave cases as well as in the wall oscillation and stationary wave cases, suggesting that the effect of the Re number cannot be represented by a simple scaling with a constant α value. Table 1 shows that the Re number scaling might be much more favourable than what is expected from low Re number studies.

References

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